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Title: Progress Report Mortandad Canyon seismic modeling

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Summary

The goal of this project is to assess site amplification for LANL through modeling of site and topography effects. Such assessment is difficult due to the lack of data documenting site effects for large normal faulting earthquakes such as the Pajarito Fault System that was found to be governing the seismic hazard at LANL. LANL site is also characterized by unique geologic settings, a series of mesa at the edge of the huge volcanic complex of the Jemez caldera. The latter has produced a series of successive and intertwined deposits of volcanic flow and sedimentary layer. Such layering of material with different elastic properties is expected to create large amplification effects magnified further by the presence at the surface of tuff materials.

In 2014, a seismic campaign was performed in the Mortandad Canyon with a network of sensors on and near a local mesa. That campaign was designed to provide experimental data to estimation and prediction of amplification and site effects at LANL. An analysis on the seismic noise records of that campaign shows evidence of amplification of the seismic amplitude for the stations on the top of the mesa. Our goal is to reproduce the effect observed (both retrieving the resonance

frequencies and amplification levels). We also plan to test if amplification effects observed for seismic noise can be extended to shaking produced by earthquakes. We are using a 3D modeling tool based on the Spectral Element Method (SEM) that is a particular type of high-order finite element modeling.
Two types of seismic sources will be considered: (1) earthquakes for purpose of seismic hazard evaluation, (2) ambient noise.

We show 2 series of numerical computations: (1) seismic waves are generated by random sources to simulate ambient noise. (2) seismic waves are planar waves to simulate a distant earthquake. We plan in the future to model rupture scenario on the Pajarito Fault System.

Path forward:

-Running more random source realization to gain confidence into the amplification effects.
-Running the ambient noise modeling in a homogeneous model with topography and a 1D layer cake model with the different units but no topography. Check consistency of the modeling results with empirical laws (e.g. Ashford & Sitar, 1997).
-Review position of receivers, and check consistency of waveforms
-Extend planar wave sources to realistic earthquake models (Brune sources)

Data and Methods.

Station Location Map

Stations: #1,#7, #10 serve as reference as they are in the canyon
Stations: #5, #6 are on the "top" of the mesa.
Stations: #2,#3,#4,#8, #9 are on the slope of the mesa.

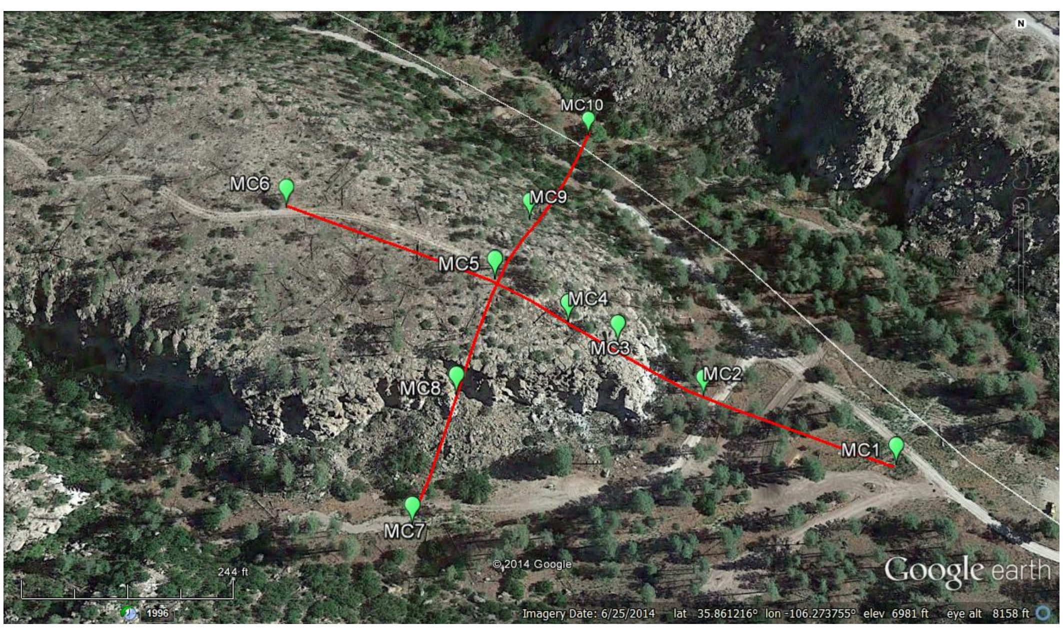


Figure 1. Satellite image of the instrumented mesa with the position of the 10 recording stations.

Ambient Noise Data

Short summary of the sentient results of Andrew and Brady paper.

Modeling

The 3D structure model (thereafter referred as seismic model) is built using the large geological and geophysical database that has been collected in the last 30 years for the LANL area (the Pajarito Basin) to develop a Geologic Framework Model (GFM) for hydrological modeling. The data of 31 regional wells completed between 1998 and 2005 have been used to constrain transport properties. A LIDAR model provides surface topography of the mesa and canyons of the area. Other geologic and on-site characterization activities have been carried out to complete the subsurface structure and stratigraphy.

We developed a model for the area surrounding the instrumented mesa. The modeled volume is 1.5 km x 1.5 km x 2.5 km in depth (see Figure 2). Surfaces describing the position of the different geologic units have been extracted from the GFM. The LANL software LaGrit was then used to develop meshes accommodating the need of the modeling: (1) hexahedral and conforming elements, (2) major geologic unit interfaces (3) and maximum size of the element. The size of element is important to determine what frequency range can be resolved by the model. Higher frequencies waves have shorter wavelengths and require finer grid to be appropriately modeled. We first requested a mesh with element size of 30 m (the code reported a maximum frequency of 7.5Hz), we just got provided with a model with element size of 15 m. The former mesh has ***165,000 elements*** and the new one

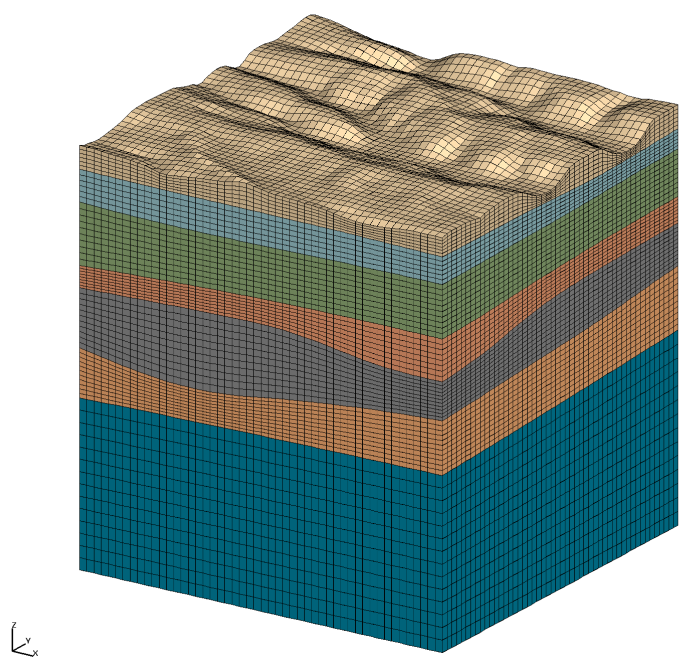


Figure 2. First mesh developed for the study with an average element spacing of 30 m. Element are color-coded according to the geologic unit they belong to. The system of Cartesian coordinates used in the modeling is featured in the lower left on the figure. X-axis corresponds to WE direction, Y-axis to NS direction, Z is positive upward.

about ***1.5M elements*** requiring 20 times more computational resources (10 for space, 2 for time). In the following, we will refer to the 7Hz-mesh as the coarser one, and the 15Hz-mesh the finer one.

We had to attribute to each geologic unit some elastic properties such as density, P-wave speed, S-wave speed and attenuation. Ideally, one wants to combine independent sources of information such as laboratory measurements, logging measurements, seismic tomography, and geologic information to produce the most accurate model. As the documentation of seismic velocities is not trivial, we came up with 3 different velocity models that are presented in Table 1.
The model 1 came from seismic data

			Model 1			Model 2			Model 3		
			Vp	Vs	ρ	Vp	Vs	ρ	Vp	Vs	ρ
1	Qtb4	Tshirege Unit 4	528	305	1700	528	305	1700	732	415	1700
2	Qtb3	Tshirege Unit 3	528	305	1700	528	305	1700	884	549	1700
3	Qtb2	Tshirege Unit 2	1558	900	1800	1558	900	1800	1128	651	1800
4	Qtb1	Tshirege Unit 1	1558	900	1800	1558	900	1800	1219	549	1800
5	Qct	Cerro Toledo fm.	1558	900	1800	1558	900	1800	1433	914	1800
6	Qbo	Otowi member	1558	900	1800	1558	900	1800	1585	732	1800
7	Tpf3	Puye – fine grain	2288	1321	2000	2288	1321	2000	2134	1232	1800
8	Tb3	Cerros del Rio basalts	2288	1321	2000	2797	1615	2200	1524	880	3000
9	Tvt2	Younger Tschicoma Dacites	2288	1321	2000	2797	1615	2200	1737	1003	2500
10	Tpf2	Puye – deep	2288	1321	2000	2288	1321	2000	2438	1407	2000
11	Tjfp	Miocene pumiceous sediments	2797	1615	2200	2288	1321	2000	1433	914	1800
12	Tb2	Younger Miocene Basalts	2797	1615	2200	2797	1615	2200	2743	1768	3000
13	Tcar	Miocene basalt with interbedded sed.	2288	1321	2000	2288	1321	2000	1100	635	2000
14	Ttc	Tesuque Fm.	2797	1615	2200	2797	1615	2200	3000	1732	2200

Table 1. Elastic properties for each of the 14 geologic units that made up the model. The number, denomination and type of rock are indicated in the first three column, then the P-wave, S-wave and density are given for each of the three models. Inversion of seismic properties (meaning that the geologic unit below has lower velocity than the unit above) are indicated by the grey shading.

The numerical code used is SPECFEM3D, which is a open-source software available on the CIG portal (CIG stands for Computational Infrastructure of Geodynamics, an effort funded by NSF to promote the use of high-performance computing solutions in geophysics). SPECFEM3D is based on the Spectral Element Method (SEM), which is a particular type of finite element with high-order basis and a diagonal mass matrix (ref). SEM modeling is well adapted to topography and 3D structure effect study as the Gauss-Lebatto-Legendre integration rule it uses ensures minimal numerical dispersion for arbitrary topography and geometries.

Measurements of wave amplification

The preparation of the synthetic waveforms and the method used to measure the amplification are the same than the ones that were used for the ambient noise analysis (Stolte, Cox, Lee, to be published). We use a modified version of the matlab script used by the Stolte et al.

The seismic waveforms computed by SPECFEM3D and output as ascii timeseries are subjected to the following treatment: (1) decimated the time series by 5 and translated into matlab datafiles (mat); (2) de-trended; (3) tapered with a Tukey window (cosine tapering); (4) filtered between 0.5 and 20 Hz; (5) transformed into a amplitude and phase spectrum vector through a FFT algorithm; (6) subjected to a Konno and Ohmachi smoothing (ref).

Three types of amplification measurement are then performed:

1. HVSR: **Horizontal to Vertical Spectral Ratio;** this is simply the ratio of the amplitude spectrum of the two horizontal components to the amplitude spectrum of the vertical component.
2. MRM: **Medium Response Method**; for each component, the medium spectrum of stations #1, #2, #7, and #10 is computed (these stations are serving as reference as they lay at bottom of the canyon). The MRM ratio is computed for each component as the ratio of the amplitude spectrum of the analyzed station to the medium spectrum of the same component.
3. SSR: **Simple Spectrum Ratio**; Only station #1 serves as reference. The SSR ratio is computed as the ratio of the amplitude spectrum to the amplitude spectrum of station #1 for each of the three components.

Another layer of analysis is performed that computes the medium and average peak spectrum. That analysis was put in place for the ambient noise study for which there are 108 time series (or realizations). As our synthetics realization is limited to 1, we decide to disregard any results of this analysis.

Ambient noise Modeling

Ambient noise modeling is performed using a random distribution of CMT sources; the position and source mechanism of the sources are random variables.

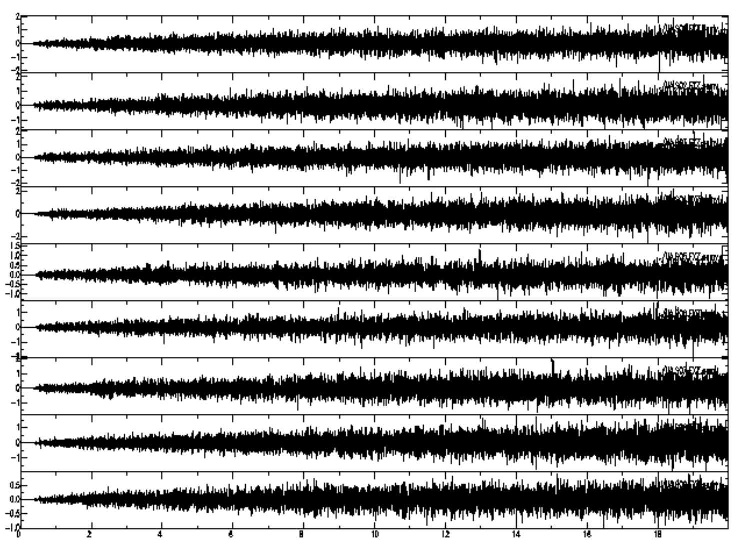


Figure 3. Example of seismic traces generated and processed to extract the topography and site effects. Shown here is the vertical component generated at the 9 network stations.

Results with the 7Hz-mesh:

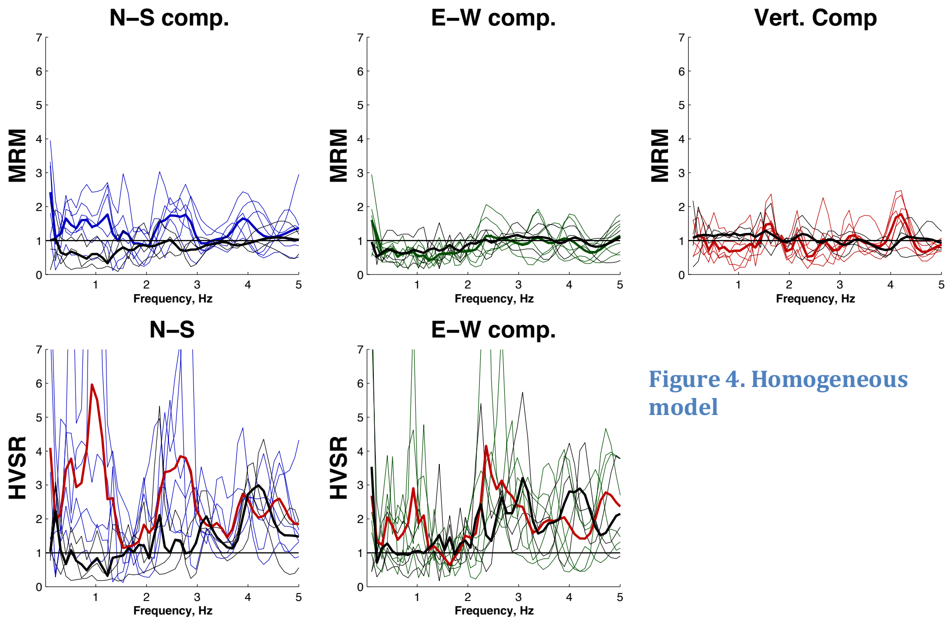
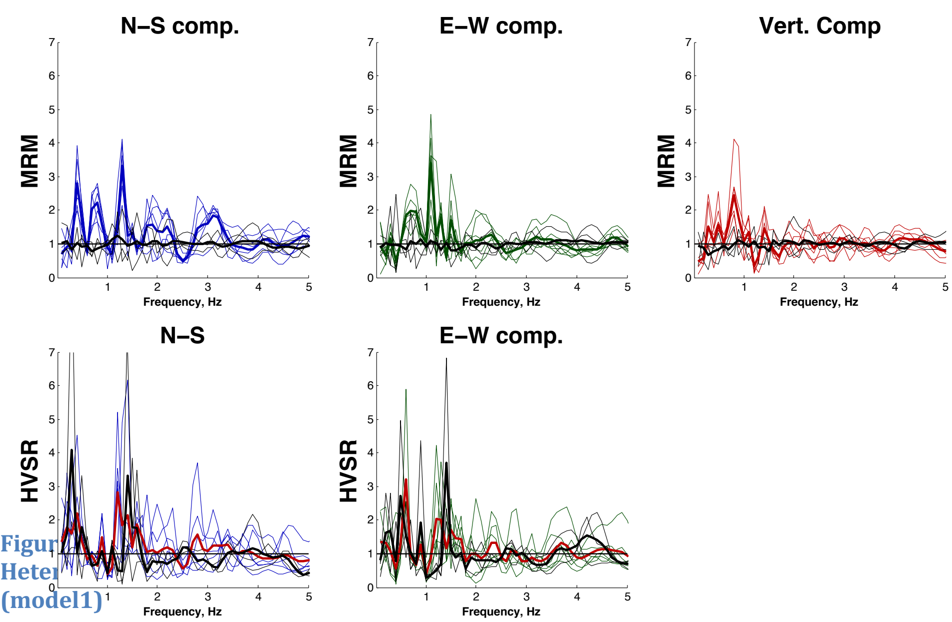


Figure 4. Homogeneous model

Sta #9



Figur
Heter
(model1)

Appendix 1:

Results with a planar wave at 2Hz polarized in the x direction (EW!)
Homogeneous models, looking only at topographic effects.

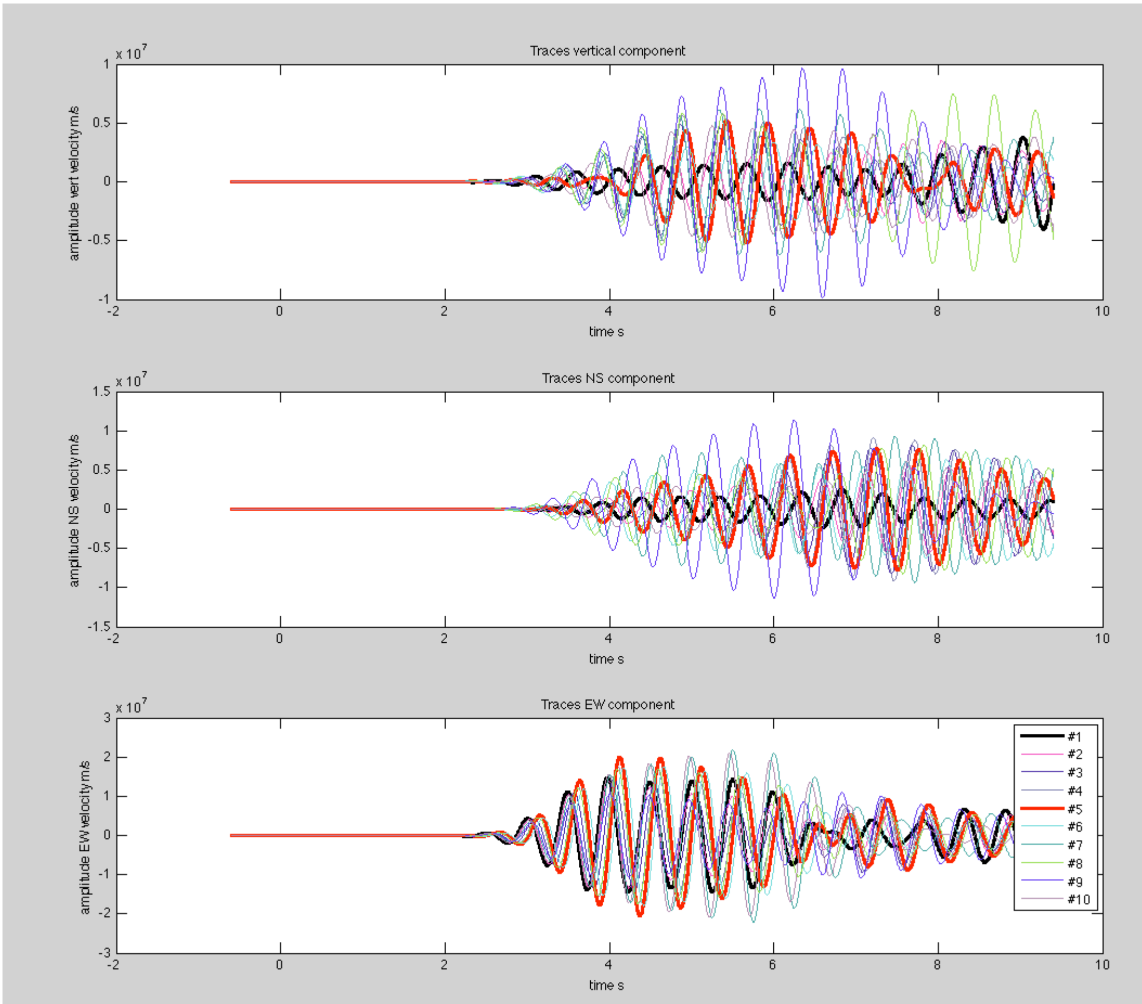
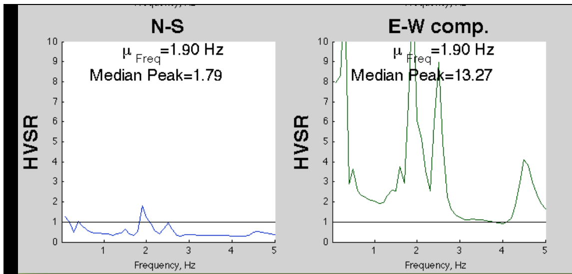
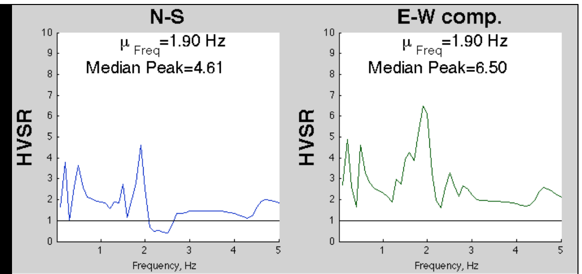


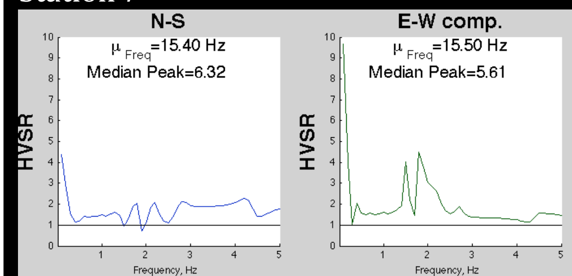
Figure 6. Velocity Records at the ten surface stations.

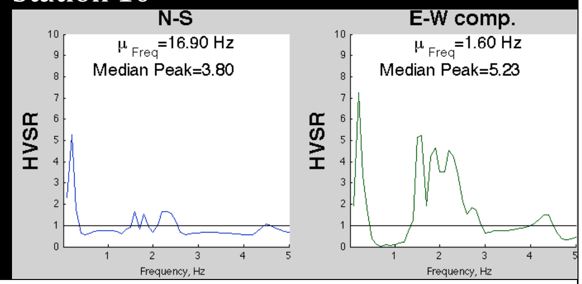
Station 1 Station 2



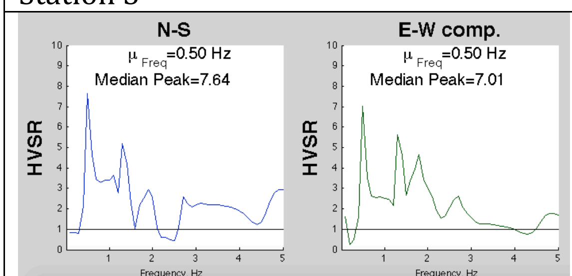


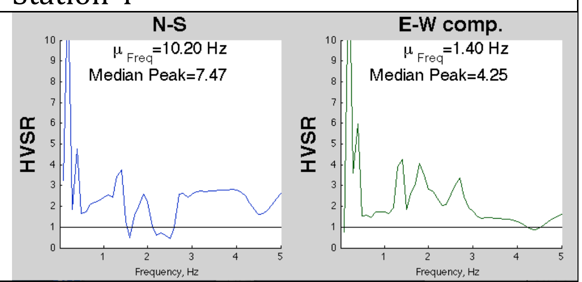
Station 7 Station 10



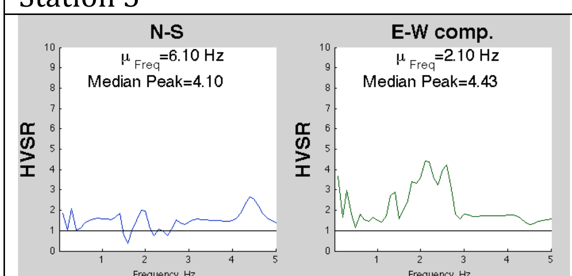


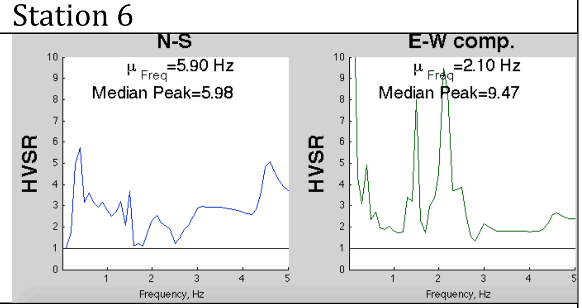
Station 3 Station 4



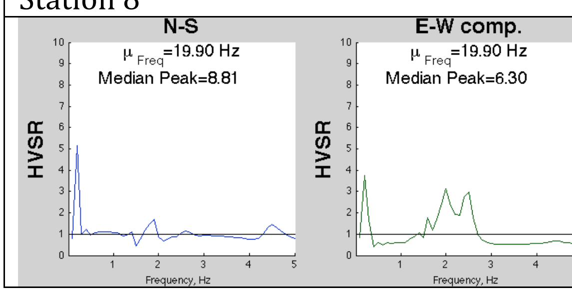


Station 5 Station 6





Station 8 Station 9



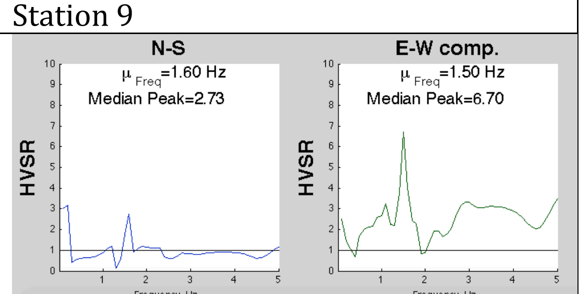
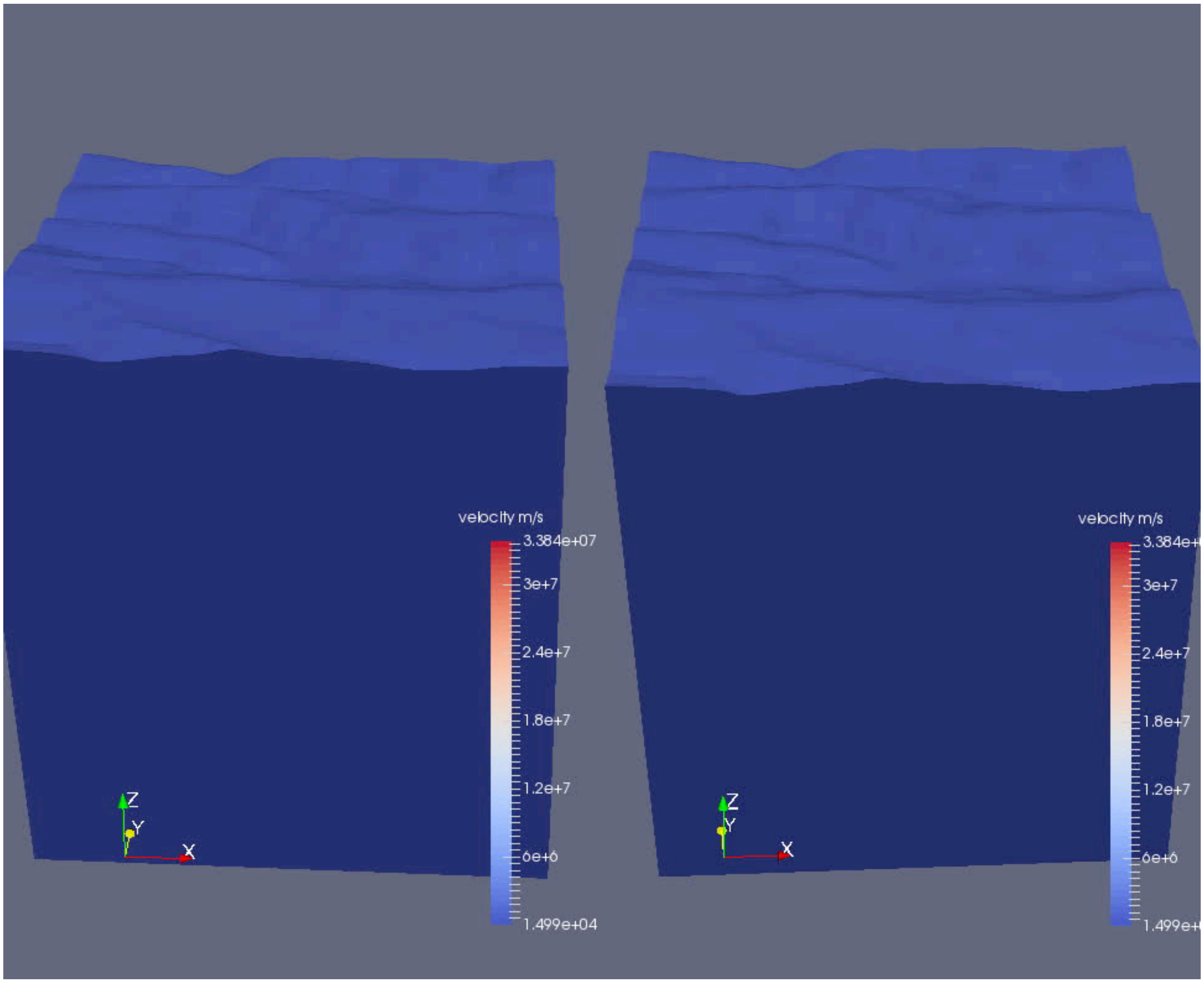


Table 2. HVSR (Horizontal Vertical Spectral Ratio) for homogeneous model, 2Hz plane wave polarized EW.

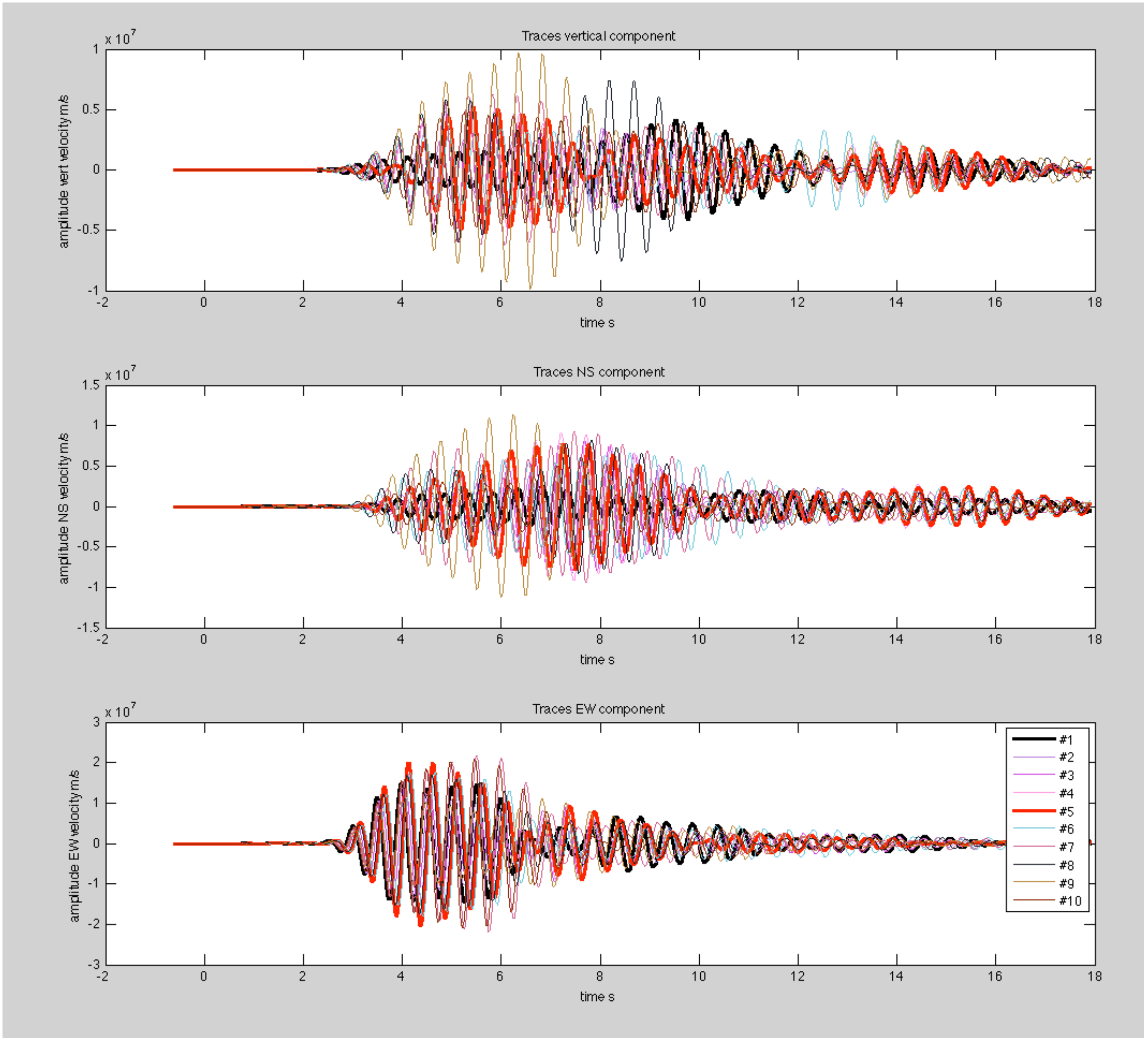
Station 1 Station 2

Table 3. MRM (Medium Response Method) for homogeneous models, 2Hz plane wave polarized in the EW direction.

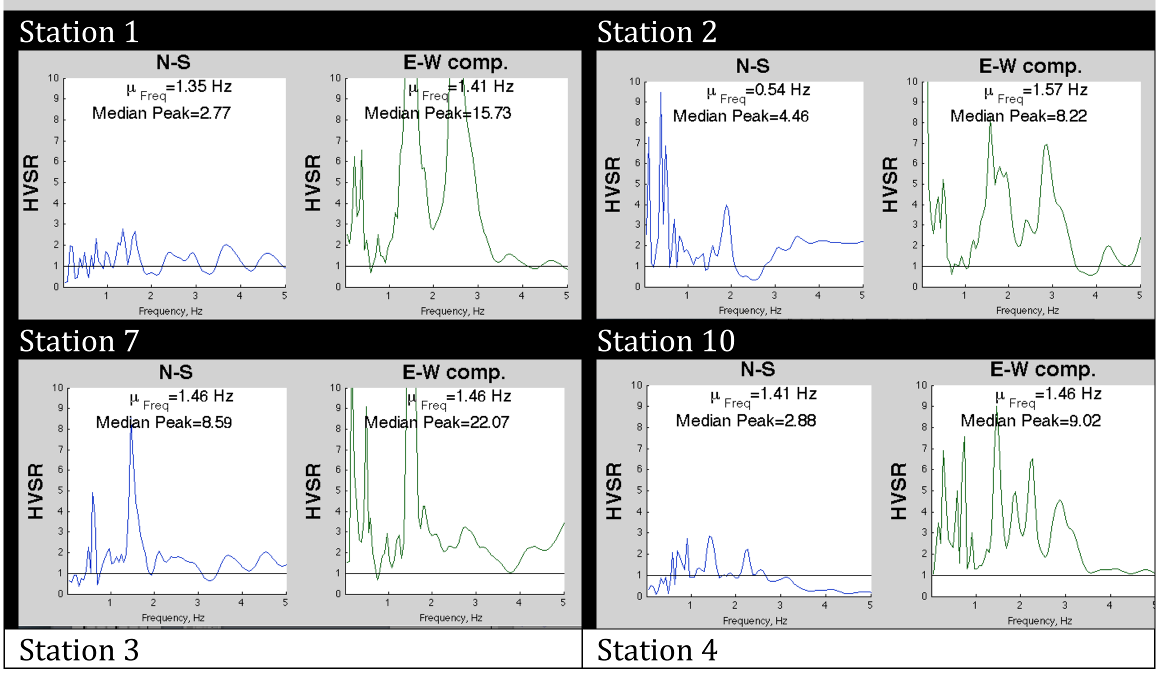
Heterogeneous model – model 3 – Adding Site Effect.



Movie of the homogeneous model (left) and heterogeneous model (right). The movie of the homogeneous model has evidence of heterogeneity.



Traces vertical component
x 10^7
amplitude vert velocity m/s
time s
Traces NS component
amplitude NS velocity m/s
Traces EW component
amplitude EW velocity m/s
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10



Station 1
N-S
μ Freq=1.35 Hz
Median Peak=2.77
E-W comp.
μ Freq=1.41 Hz
Median Peak=15.73
Station 2
N-S
μ Freq=0.54 Hz
Median Peak=4.46
E-W comp.
μ Freq=1.57 Hz
Median Peak=8.22
Station 7
N-S
μ Freq=1.46 Hz
Median Peak=8.59
E-W comp.
μ Freq=1.46 Hz
Median Peak=22.07
Station 10
N-S
μ Freq=1.41 Hz
Median Peak=2.88
E-W comp.
μ Freq=1.46 Hz
Median Peak=9.02
HVSR
Frequency, Hz
Station 3
Station 4

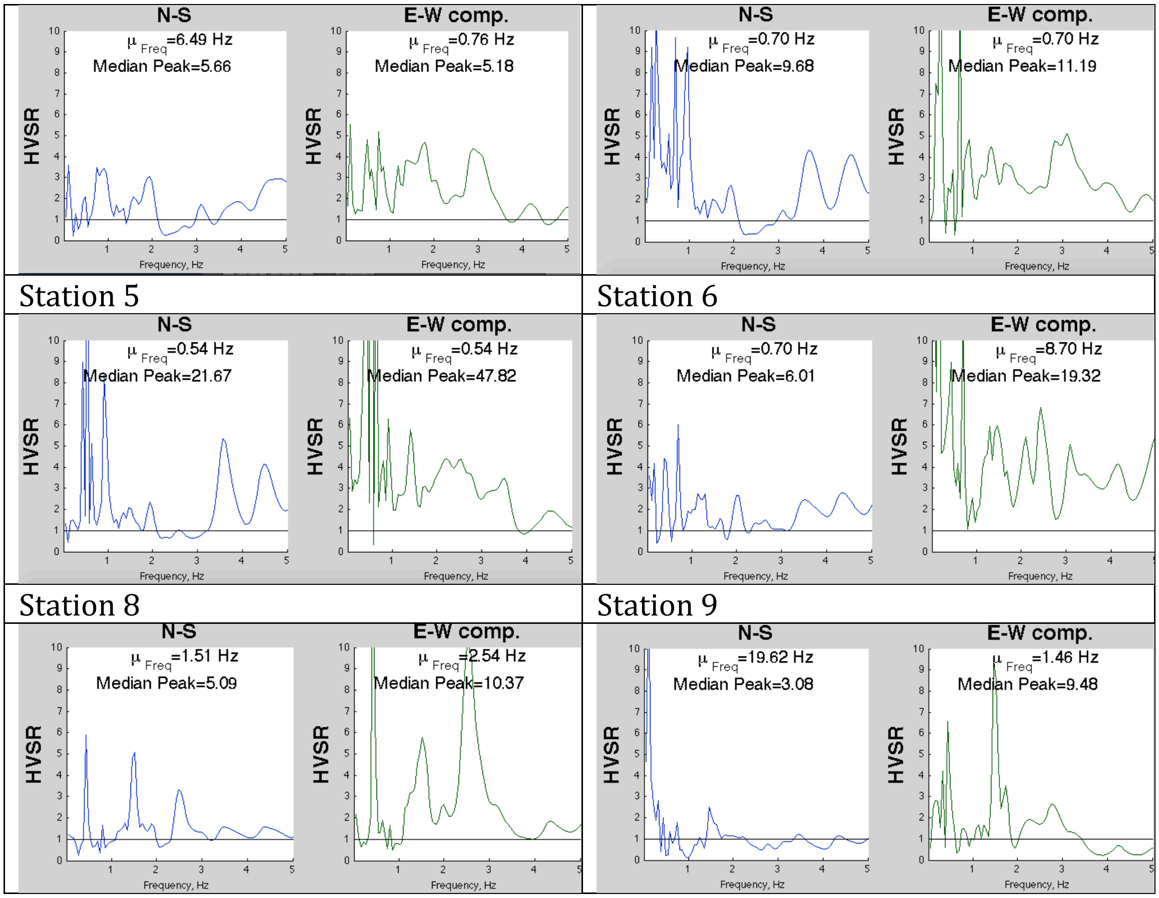
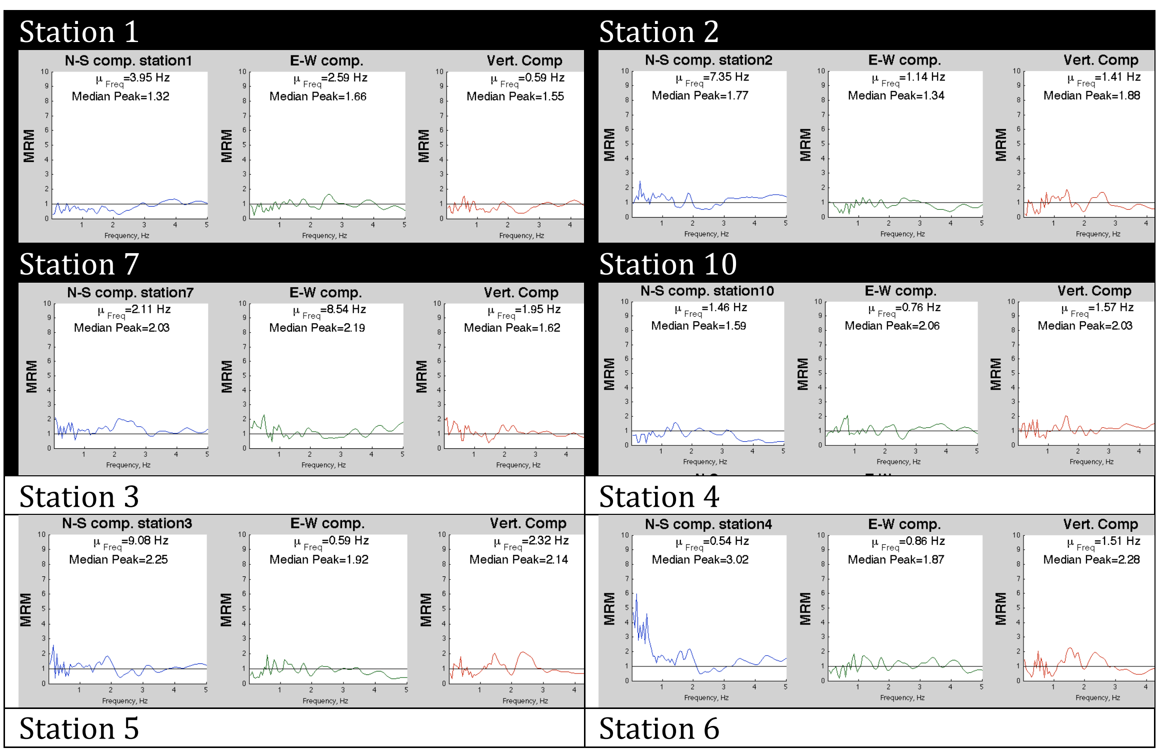
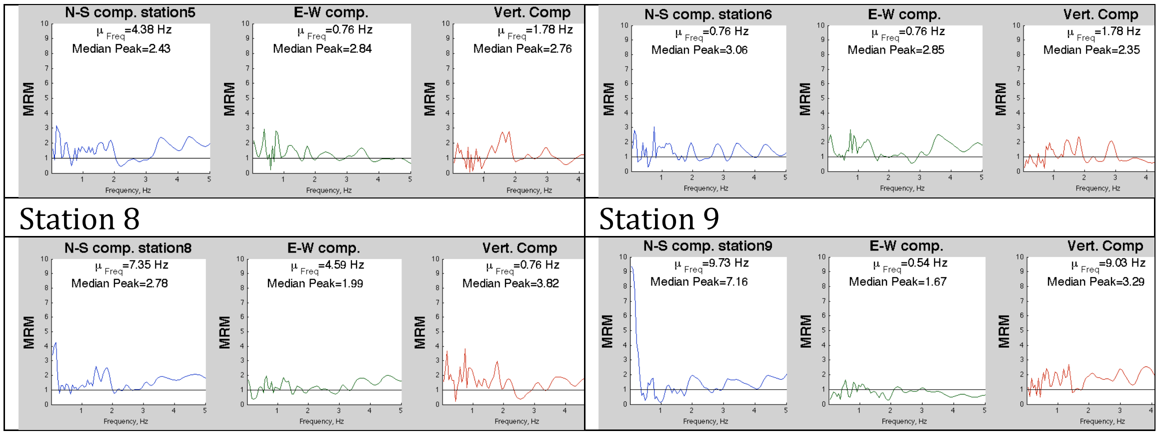


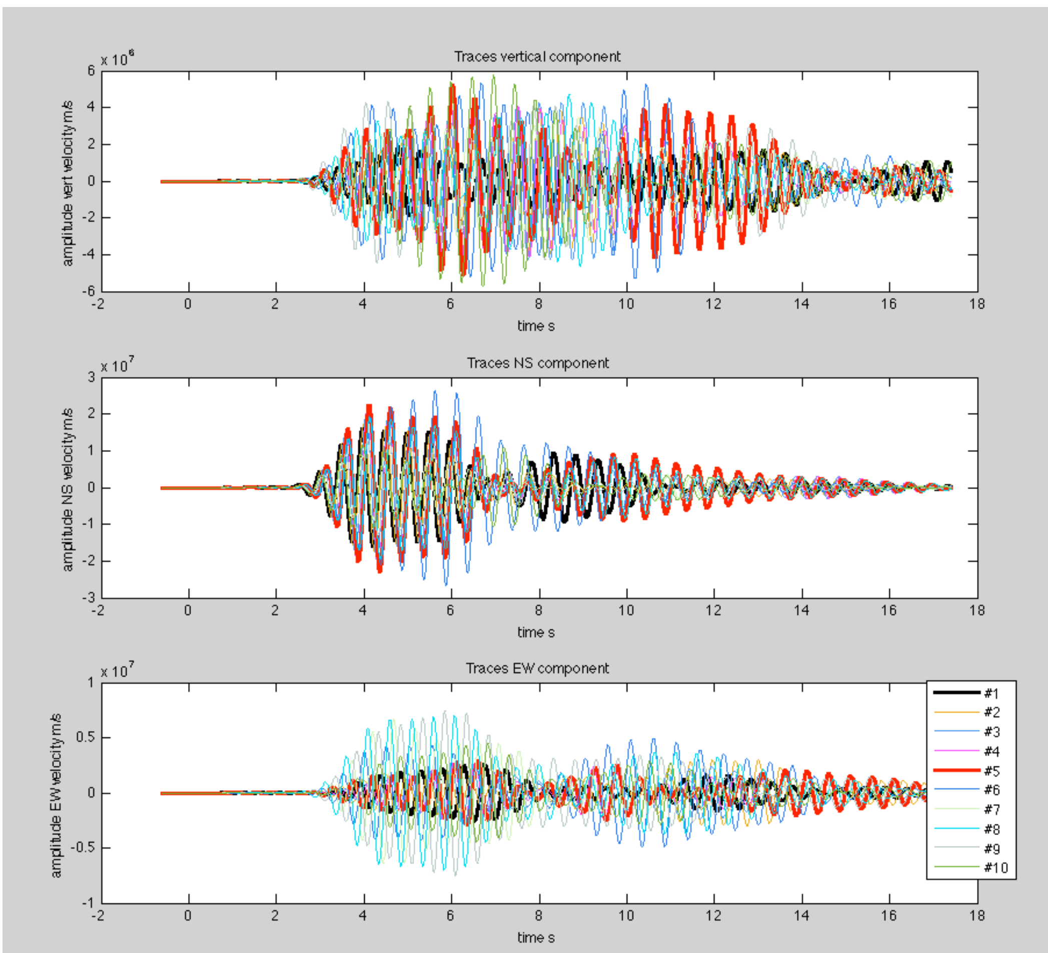
Table 4. HVSR for heterogeneous model; 2Hz plane wave polarized in the EW direction

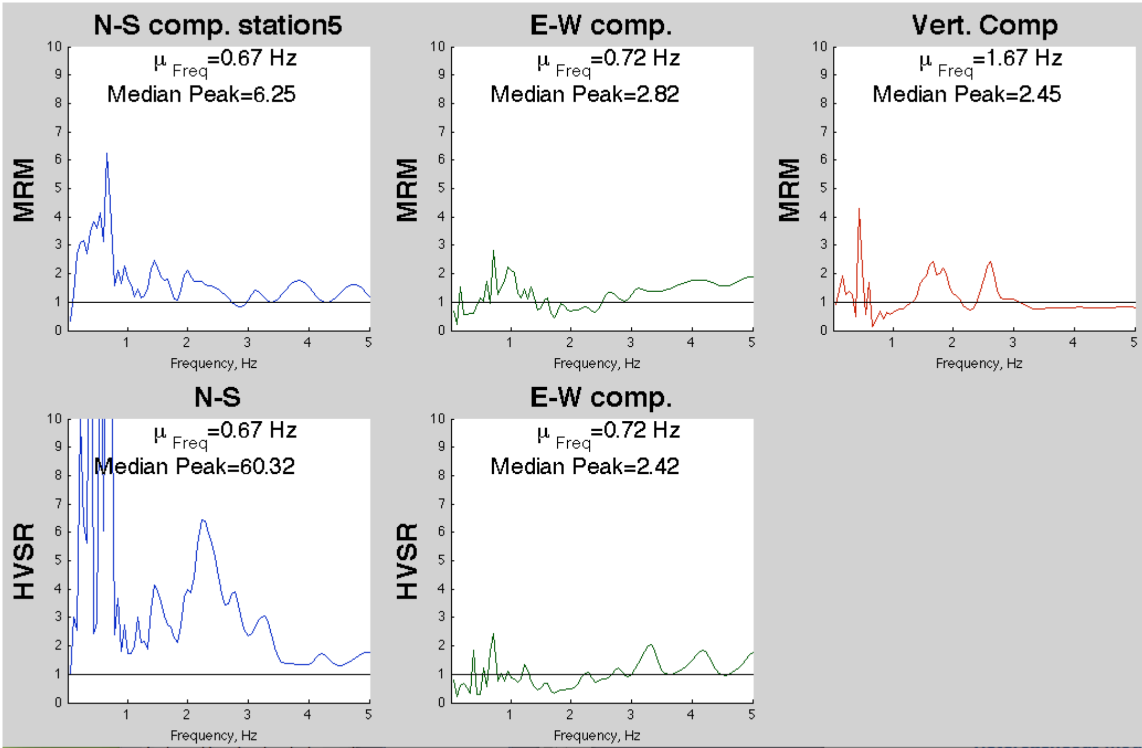




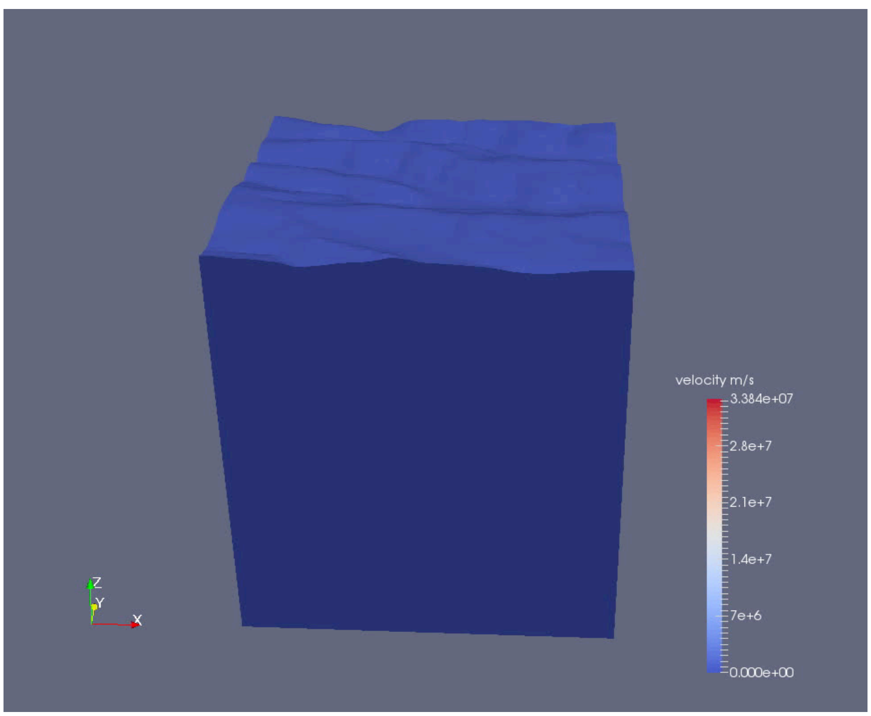
Results with a plane wave polarized in the NS direction.

Homogeneous model





Heterogeneous model



Homogeneous model

Figure 7. Results of MRM measurements for 120 random sources and the 10 stations at the top.